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ANALYSIS OF RATE AND DYNAMIC TESTS ON THE LITTON (Canada) CANADIAN STRAPDOWN GYROSCOPE (CSG-2)

by

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DEFENCE RESEARCH ESTABLISHMENT OTTAWA
TECHNICAL NOTE 88-20

PCN
041LJ

April 1988
Ottawa

89-06299/

Abstract

Results of rate and dynamic tests on the Litton (Canada) Canadian Strapdown Gyroscope (CSG-2) are presented. Tests include scale factor stability, scale factor deviation at constant rate over a rate range of ± 1 radian/sec, rate change (transient) tests as well as evaluation of the effects of temperature changes. Instrument design characteristics and suggestions for future improvements are discussed.

Résumé

Les résultats des test de régime et de dynamique du gyroscope Canadien CSG-2 sont présentés. Les tests couvrent la stabilité du facteur d'échelle, la déviation du facteur d'échelle pour des vitesses jusqu'à ±1 radian/sec, les changements de vitesses transitoires ainsi que la sensibilité aux changements de température. Les caractéristiques de l'instrument sont discutées et des suggestions d'améliorations futures sont présentées.

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1.0 BACKGROUND

Results of extensive laboratory tests on the Litton (Canada) Canadian Strapdown Gyroscope (CSG-2) were presented in DREO Report #914 (September, 1986).

This report details the results of further analysis of the data, particularly with respect to Scale Factor deviation and torquer magnet thermal sensitivity; areas which were left previously unexplored.

A performance summary of the CSG-2 gyroscope is provided.

1.1 INTRODUCTION

The CSG-2 is a two-degree-of-freedom (TDF), tuned rotor gyroscope (TRG) suitable for use in a wide variety of strapdown attitude-sensing applications. Details on the design features and mechanization of the instrument are contained in DREO Report # 914, 'Test Evaluation of the Litton (Canada) Canadian Strapdown Gyroscope (CSG-2)'.

As described in the report, the unique flexure mechanization and the use of sophisticated laser welding techniques have resulted in a highly reliable, stable and inexpensive gyroscope.

Table 1-1 lists the specifications to which the gyroscope was designed. Note the very high torquer scale factor and the low random (uncompensatable) drift.

Table 1-2 details the various properties and materials of the CSG-2.

A photograph of the gyroscope is shown in Figure 1-1.

1.2 REVIEW OF STATIC, RATE AND DYNAMIC TEST RESULTS

Results of static tests performed on the CSG-2 to determine time constant, tuned speed, figure-of-merit and the drift coefficients and compliance terms are shown in Table 1-3.

Note that the random drift of the instrument is less than 0.005 deg/hr, showing exceptional stability.

Torquer scale factors of 1600 deg/hr/mA about each axis are an indication of the wide dynamic range of the instrument.

PARAMETER	DESIGN GOAL	TYPICAL INERTIAL GRADE GYRO SPECIFICATIONS	COMMENTS
RANDOM DRIFT (°/HR)	< 0.005	< 0.005	
NON-G SENSITIVE DRIFT (°/HR)	< 3.0	< 4.0	SYSTEM COMPENSATION
NON-G DRIFT REPEATABILITY (°/HR)	< 0.01	< 0.007	TURN ON TO TURN ON
NON-G DRIFT TEMPERATURE SENSITVITY (°/HR/°F)	< 0.01	< 0.014	140°F to 165°F
G-SENSITIVE DRIFT (R.S.S.) (°/HR/G)	<10.0	< 0.5	SYSTEM COMP. WITH G LEVEL INFORMATION
G-SENSITIVE DRIFT REPEATABILITY (°/HR/G)	< 0.02	< 0.02	TURN ON TO TURN ON
G-SENSITIVE DRIFT TEMP. SENSITIVITY (°/HR/G/°F)	< 0.05	< 0.04	140°F TO 165°F
Wheel speed (Hz) (resonant frequency)	100Hz ± 5Hz (4 pole motor driven by 400Hz)		
Torquer scale factor (°/hr/mA)	> 1400		
Torquer resistance	< 50 ohms		
Torquer axis alignments	< 19.39 mRad		
Motor power, start run	< 8 watts < 3 watts		
Wheel run-up time	< 30 sec.		
Operating temperature	155°F		

Table 1-1 CSG-2 Design Specifications

		CSG-2
Suspension: -		
Hub:	Material	Vascomax 300CVM
Gimbal:	Material	Vascomax 300CVM
:	Type	1: flanged - 2 piece
Flexures:	Type	EDM'd from Gimbal
:	Material	Vascomax 300CVM
:	Blade	Flat crossed
:	Attachment	Bottom - Bottom
Rotor: -		
Housing:	Material	Hyperco 50
:	Configuration	1 piece
:	No. of Spacers	None
:	Magnets	Inner
:	No. Parts	3
Magnets:	Material	Placovar or Pt. Co.
:	Type	Ring
:	No. Rings	2
Coil & Support: -		
Support Ring:	Material	Te. Cu.
Torquer Coil:	Wire	
:	No. Turns	270
:	Resistance	56.5
:	Core	No
:	Coil Wind	Dry
:	Adhesive	
Case:		CSG-2
Shaft:		CSG-2
Motor:		G1200

Table 1-2 CSG-2 Materials and Properties

	CSG-2
Weight (gms)	350
Size (in^3)	3.3
Rotor Speed (Hz)	95 - 121
H ($g\text{-}cm/sec^2$=dyn cm-sec)	45,300 at 102.6 Hz
Torquer Scale Factor @ 100 Hz (°/hr/mA)	1765
Torquer Power @ 30°/sec	0.20 (design)
Max. Rate 40W/axis	427°/sec
SS. Rate 10W/axis, °/sec	213°/sec
G- Capability:	80
FM =	240
T.C. (sec)	110
Bias, Repeat (°/hr, 1 σ)	0.0065
Bias Temp. Sens. (°/hr/°F)	0.0052 (avg of 2)
G-Sens Repeat (°/hr/g,1 σ)	0.0073
G-Sens Temp. Sens. (°/hr/°F)	0.019 (avg of 2)
Random Drift (°/hr,1 σ)	0.0025
Res. Freq., G-sens (Hz/g)	0.09/ .12
Qx, Qy (°/hr/G)	0.93
Motor Power (W)	1.7
Run-up Time (sec)	8
Aniso. °/HR/g^2	0.044 & 0.33

Table 1-2 (Cont'd)

Figure 1-1 CSG-2 Gyroscope

PARAMETER	
Torquer scale factor K_x	1642 deg/hr/mA
K_y	1671 deg/hr/mA
Torquer axis misalignment	-850 Arc sec.
	-1373 Arc sec.
Motor start power at 12 V_{RMS}	8.0 Watts
Motor run power at 7.5 V_{RMS}	2.0 Watts
Run-up Time RUT	8.2 Sec
Pickoff scale factor K_{POX}	0.716 V_{RMS}/mrad
K_{POY}	0.720 V_{RMS}/mrad
Pickoff Offset x	-3.2 Arc sec.
y	-4.7 Arc sec.
Figure of Merit F_m	240
Tuned Frequency F_r - Mechanical	105.5 Hz
- Electrical	422 Hz
Time Constant	108 sec.
Random Drift	
$X_{horizontal}$	0.0017 deg/hr/(1σ)
$Y_{horizontal}$	0.0014 degr/hr(1σ)
Non g-sens drift BD_x	-1.429 deg/hr
(bias) BD_y	+5.136 deg/hr
g-sens drift	
MU_x	+ 3.351 deg/hr/g
MU_y	+ 3.357 deg/hr/g
Q_x	-1.635 deg/hr/g
Q_y	+1.551 deg/hr/g
g^2-sens drift	
$D(x)_{xx}$	+ 0.016 deg/hr/g^2
$D(y)_{yy}$	+ 0.022 deg/hr/g^2
TEMPERATURE	69^0C

Table 1-3 CSG-2 (S/N 003) Test Results Feb 87
Using DREO RL-2 Loop

The effect of temperature on the drift coefficients of the instrument was determined from multi-position tests performed at various gyroscope temperatures; 50°C, 69° (normal operating temperature) and 80°C. Typical results are shown in Table 1-4. It can be seen that the effect of temperature changes on the drift coefficients of the gyro seems to be very small and is within the measurement error of the test system.

Temperature sensitivity of the gyro bias drift is less than 0.02 deg/hr/°C in both X and Y axes.

Drift repeatability for both non-g and g-sensitive drifts was less than 0.01 deg/hr/g.

Rate and dynamic tests were performed on the CSG-2 to determine scale factor deviation and stability as well as the effects of rate transients and temperature changes.

Scale factor stability of the CSG-2 is better than 30 ppm and scale factor deviation is approximately 1800 ppm over a rate range of $\pm$ 1 rad/sec.

2.0 ANALYSIS OF RATE AND DYNAMIC TESTS

2.1 TEST DESCRIPTION

Strapdown tests were conducted to evaluate instrument performance under rate and dynamic conditions.

The rate and dynamic tests described here were performed with an analog rebalance loop (RL-2) designed at DREO for a variety of strapdown system applications. The specifications are shown in Table 2-1. A detailed description of the loop can be found in DREO Tech Note TN 86-10. The design is registered as a DND invention under file number 1416-86-001 (D Pat A), dated 17 January 1986.

The DREO rebalance loop, designated RL-2, consists of two direct-axis, analog torque-to-balance (ATBL) loops. For constant rate tests, no cross-axis loops (to compensate for acceleration) were used. (Cross-axis acceleration compensation has been implemented into the design and designated RL-3 for future tests.)

Parameter/Temperature	50°C	69°C	80°C
BD_x(deg/hr)	-1.446	-1.429	-1.539
BD_y(deg/hr)	5.335	5.136	4.983
$D(X)_x$(deg/hr/g)	2.863	3.351	3.704
$D(X)_y$(deg/hr/g)	- 1.623	-1.635	-1.650
$D(Y)_y$(deg/hr/g)	2.861	3.357	3.689
$D(Y)_x$(deg/hr/g	1.528	1.551	1.546
$D(X)_{xx}$(deg/hr/g^2)	0.008	0.016	0.011
$D(Y)_{yy}$(deg/hr/g^2)	0.002	.002	-0.028

Table 1-4 Temperature Sensitivity of Drift Coefficients

PARAMETER	UNITS	HIGH RATE	LOW RATE
Range	deg/sec	$\pm$ 60	$\pm$ 4
Bandwidth -3dB Closed loop	Hz	25	0.7
Linearity Closed loop	ppm	$\pm$15	$\pm$3
Stability Closed loop	mrad	$1x10^{-4}$	$1x10^{-4}$
Noise Closed loop	mrad (rms)	$5x10^{-5}$	$5x10^{-5}$
Settling Time to 10ppm	sec	0.5	8
Current Range	mA	$\pm$130	$\pm$7
Scaling Resistors	OHMS	30	1030
Proportional Gain at pickoff	mA/Volt (rms)	7	0.2
Integrator Corner Freq.	Hz	3.3	0.3
Bandwidth open loop	Hz	52	52
Phase at Nutation Freq	deg	-180	-180

Table 2-1 DREO RL-2 Bi-level Analog Rebalance Loop Specifications

The direct-axis loops compensate for constant angular input rates. When an input rate is applied to the case of the gyroscope, the pickoffs sense the resulting change in attitude between the case axis and the rotor axis. The pickoff output signals are fed to the analog rebalance loop which then generates a precision current which is fed to the case-fixed torquer coil of the gyroscope as a direct rebalance current. This provides the restoring torque to maintain the gyro at it's null position. The rebalance currents to the torquers are also sampled as a measure of input rate and this provides the readout mechanization. The sampling instruments in the DREO laboratory are high-precision digital voltmeters which sample the voltage across an oil-filled precision sampling resistor in each arm of the rebalance loop. These meters are tied directly into a computer-controlled data collection system.

2.2. TEST DATA

The stability and linearity of the gyro scale factor was measured. In addition, the effects of torquer current (i.e. rate) changes on the scale factor including both transient and steady-state temperature effects were examined.

2.2.1 Scale Factor Stability

The stability of the torquer scale factor is determined by rotating the gyro about each of its input axes, in turn, at a constant rate for several hours while measuring the torquer current. The peak to peak variation in the current determines the scale factor stability. Figure 2-1 shows scale factor deviation for the y-axis at a rate of 20 deg/sec over a period of approximately 12 hours. The scale factor stability is 30 ppm.

2.2.2 Scale Factor Linearity

Linearity of the scale factor over the entire rate range of the closed-loop gyroscope was measured. The closed-loop CSG-2 instrument goes through large current changes in the torquer coils due to changes in input rates about each axis. The effects of torquer heating due to current changes can be significant resulting in changes in torquer scale factor and, thus, a deviation in scale factor over the dynamic range of the gyroscope. Scale factor non linearity is determined by rotating the instrument at successive constant rates over the entire dynamic operating range of the gyroscope. In the case of the CSG-2, this was $\pm$ 1 rad/sec. The scale factor at each rate is determined and deviation from nominal scale factor is plotted. Figure 2-2 is a plot of scale factor deviation for the y-axis. Scale factor deviation is approximately 1800 ppm over the rate range. This deviation is suspected to be due almost exclusively to torquer heating effects. This can be shown through scale factor deviation tests performed at various controlled gyro temperatures. As can be seen in Figure 2-3, the scale factor varies by 500 ppm/^{o}C change in torquer temperature. This agrees with calculations done on the

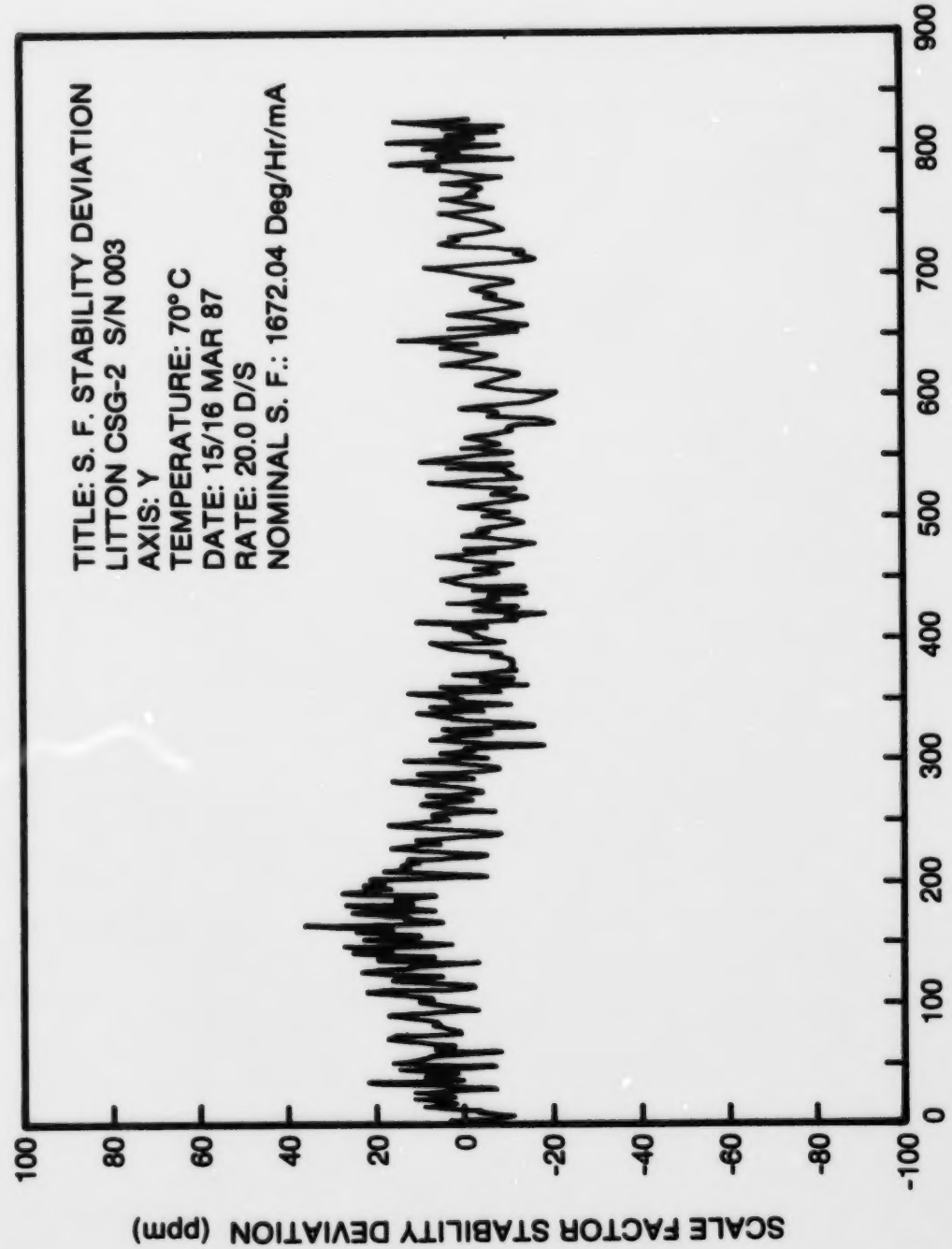

Figure 2-1. Scale Factor Stability Deviation

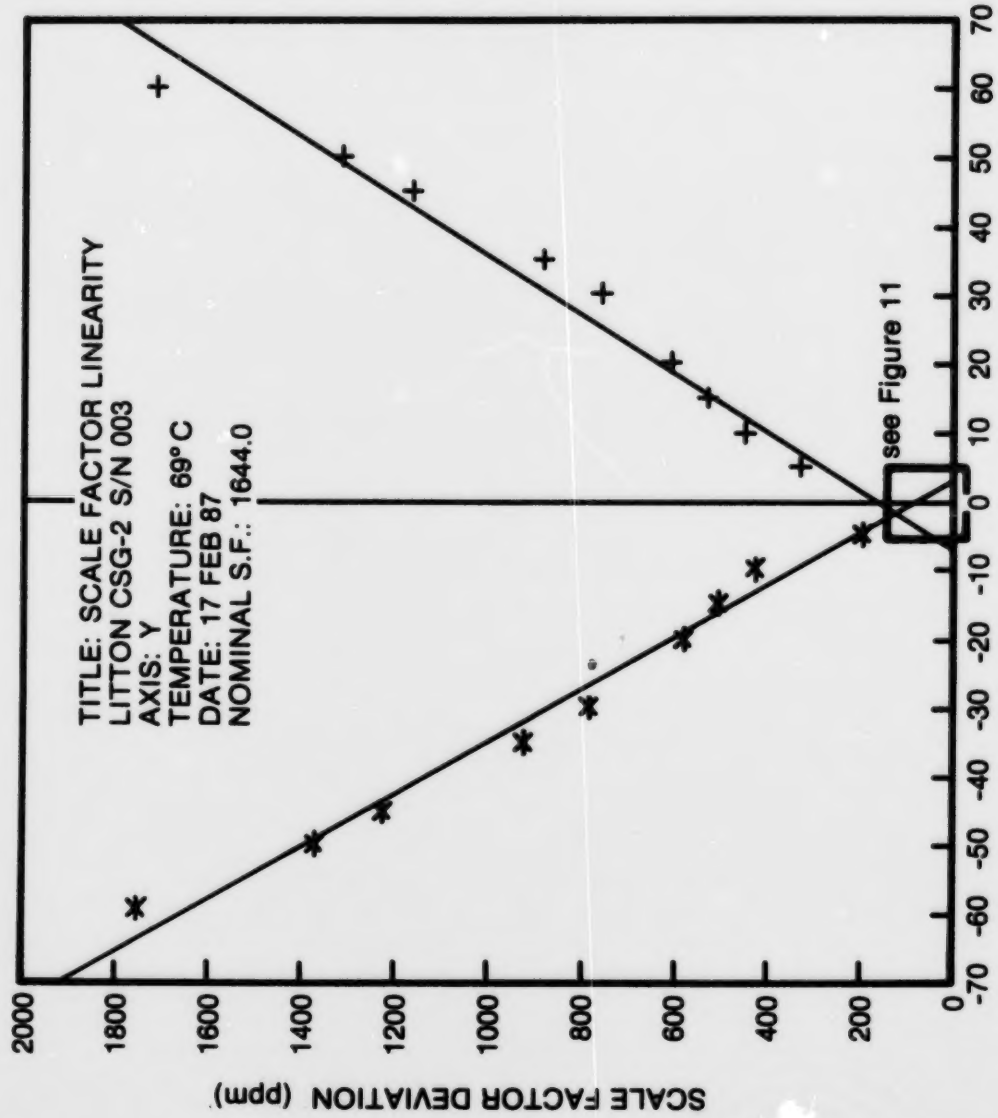

Figure 2-2. Scale Factor Deviation; ±1 rad/sec

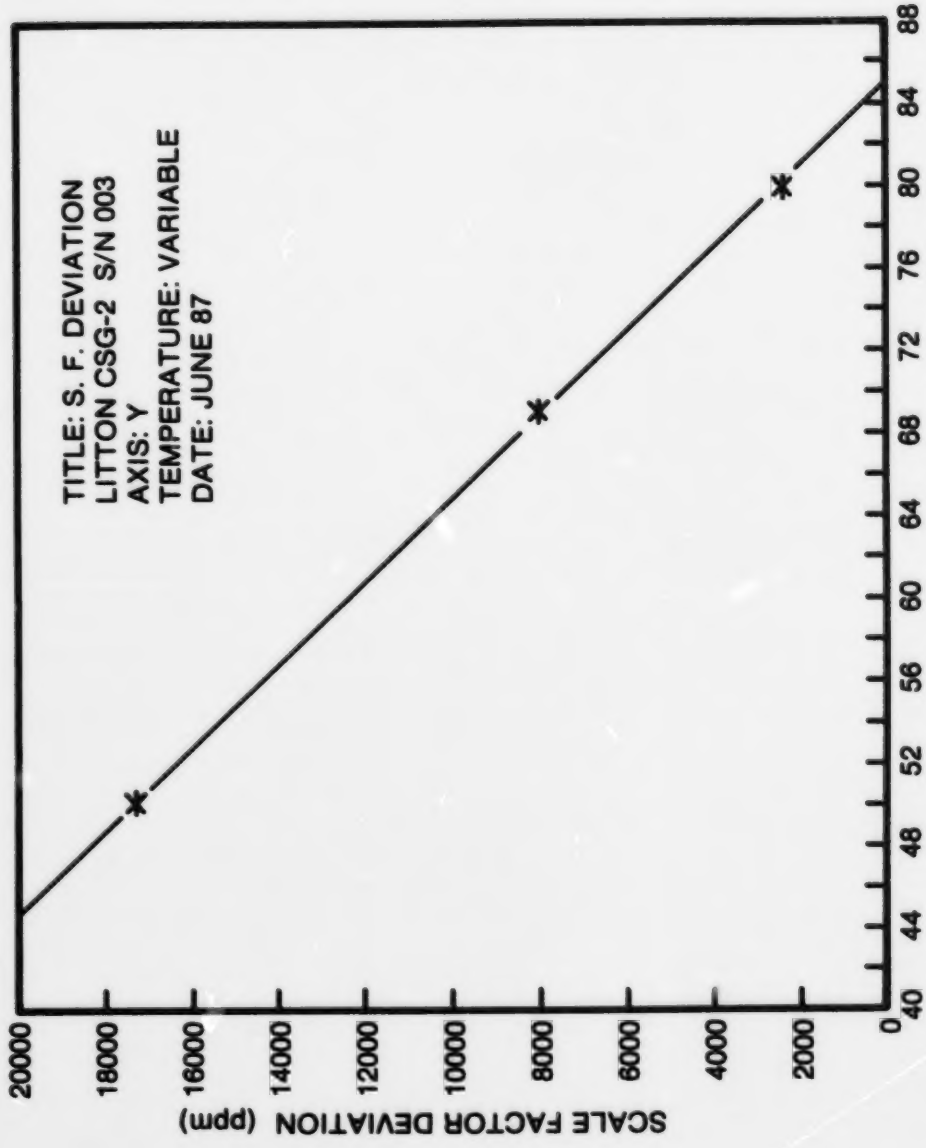

Figure 2-3. Scale Factor Deviation Versus Temperature

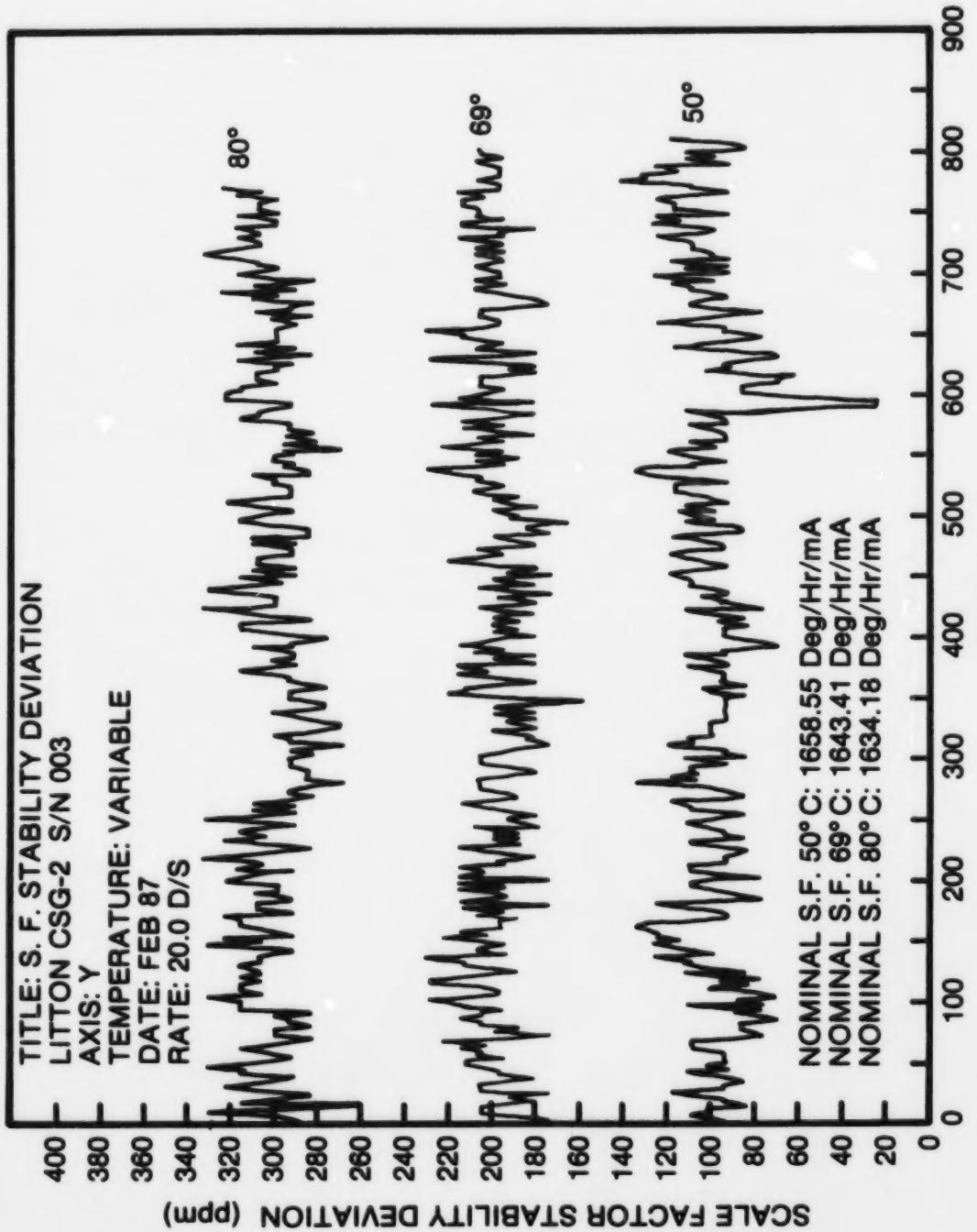

Figure 2-4. Scale Factor Stability versus Temperature

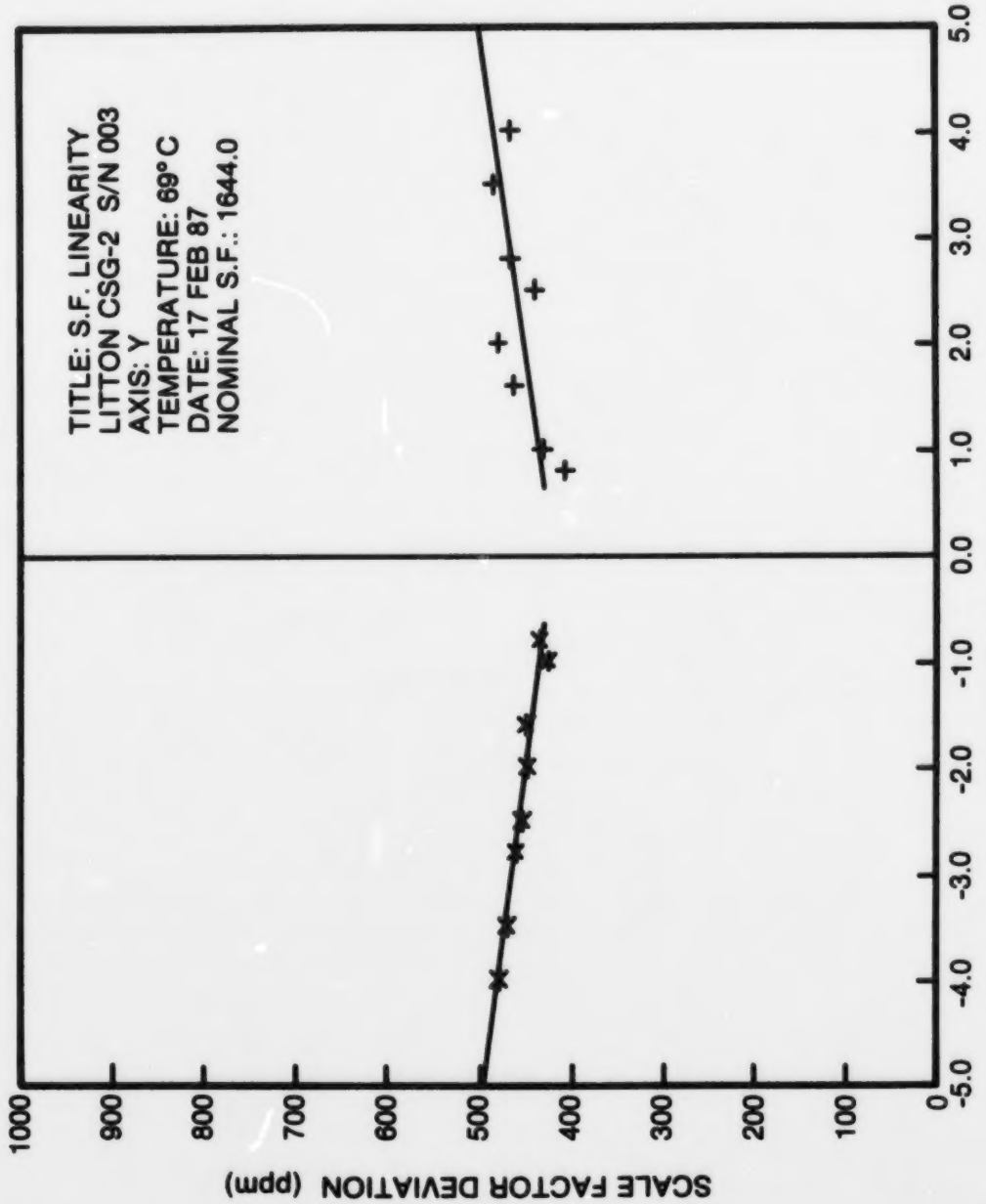

Figure 2-5. Scale Factor Deviation at Low Rate

platinum cobalt magnet material and the changes in magnetic field strength due to temperature as described in the next section. Figure 2-4 shows that although scale factor deviation is affected by temperature, scale factor stability is not. Scale factor stability at operating temperatures of 50, 69 and 80°C is plotted. Scale factor linearity at low rates is also significant. Figure 2-5 shows scale factor deviation from 0 to ± 5 deg/sec.

2.2.3 Rate Changes

The effect of changes in input rate has already been shown to produce changes in torquer scale factor of a predictable and repeatable nature. Another aspect is the transient effects of these changes.

In order to characterize the effects, the gyro was alternately 'stepped' from one rate to another and back again at regular intervals. The effects on scale factor were measured.

Figure 2-6 shows successive steps between 25 deg/sec and 45 deg/sec. Note the transient in the scale factor of approximately 600 ppm over an interval of several minutes, settling to a stability of 30 ppm. An expanded view of single steps is shown in Figures 2-7 and 2-8. Note, also, the absolute change in scale factor between the two rates which is in agreement with Figure 2-2. Further analyses of the dynamic effects are discussed in the next section.

2.3 THERMAL ANALYSIS

The extensive tests on the CSG-2 gyroscope have shown with certainty that the temperature sensitivity of the CSG-2 torquer scale factor is almost totally due to the properties of the magnets employed in the instrument.

Original manufacturer's specifications for the platinum cobalt magnet material employed in the early prototype CSG-2 gyroscopes called for a temperature sensitivity of -0.015% per degree celsius (150 ppm/°C). In actual fact, recent calculations have shown this sensitivity to be 0.05% per degree celsius (500 ppm/°C). This was determined through the use of a computer program called SPICE, developed by Litton, Canada. The CSG-2 was thermally modelled as a circuit consisting of 43 resistors, 3 current sources and 26 nodes. The analysis showed that a CSG-2 gyroscope containing two platinum cobalt torquer magnets has a drop in magnetic field strength of 550 ppm per degree Celsius change in magnet temperature.

Testing of four prototype CSG-2 gyroscopes resulted in an average temperature sensitivity in scale factor of -547 ppm/°C with a standard deviation of 24 ppm.

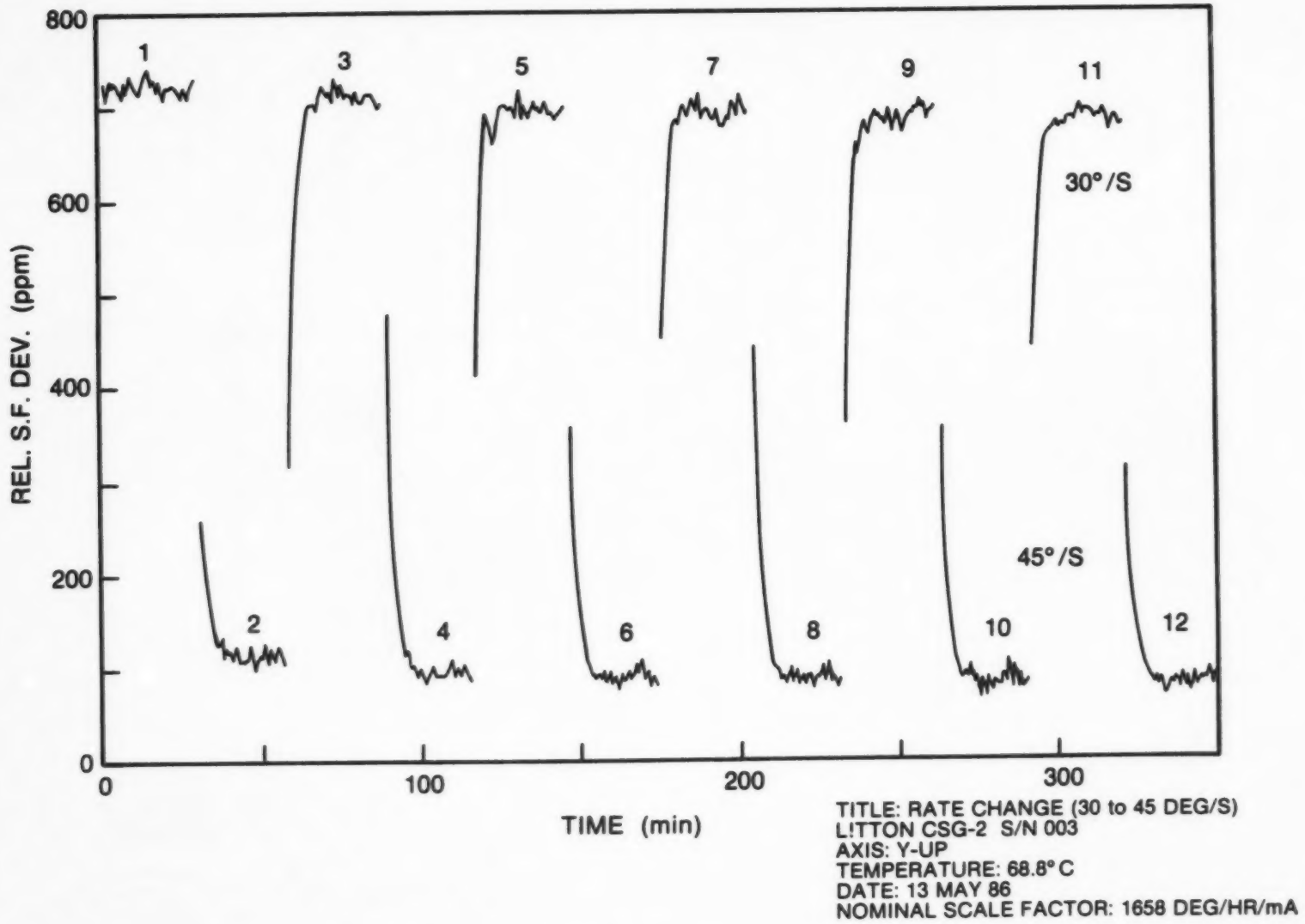

Figure 2-6. Rate Changes, 30-45 deg/sec.

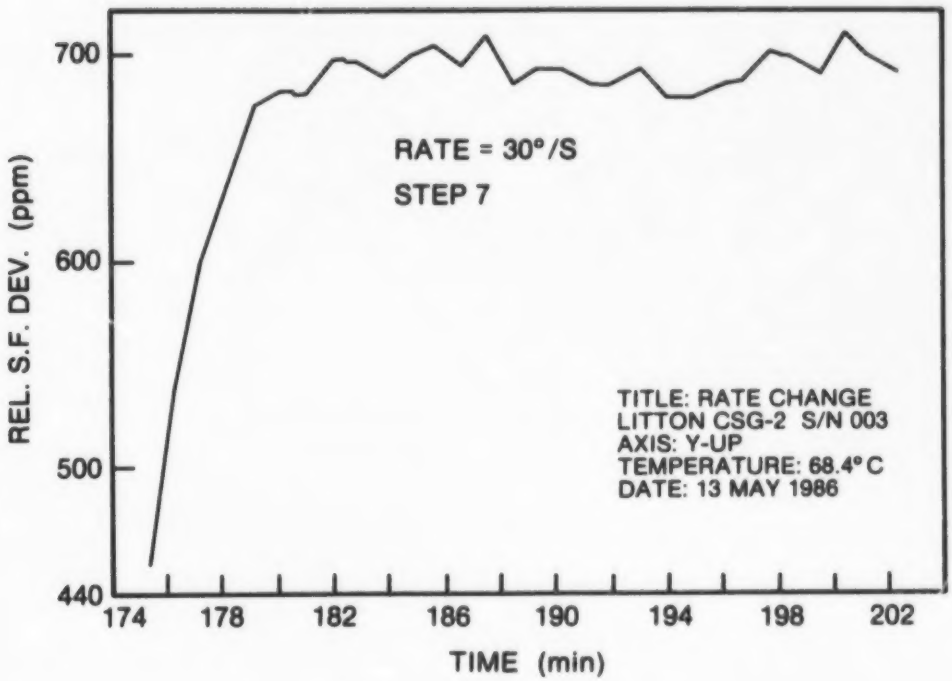

Figure 2-7. Single Rate Step, 45-30 deg/sec.

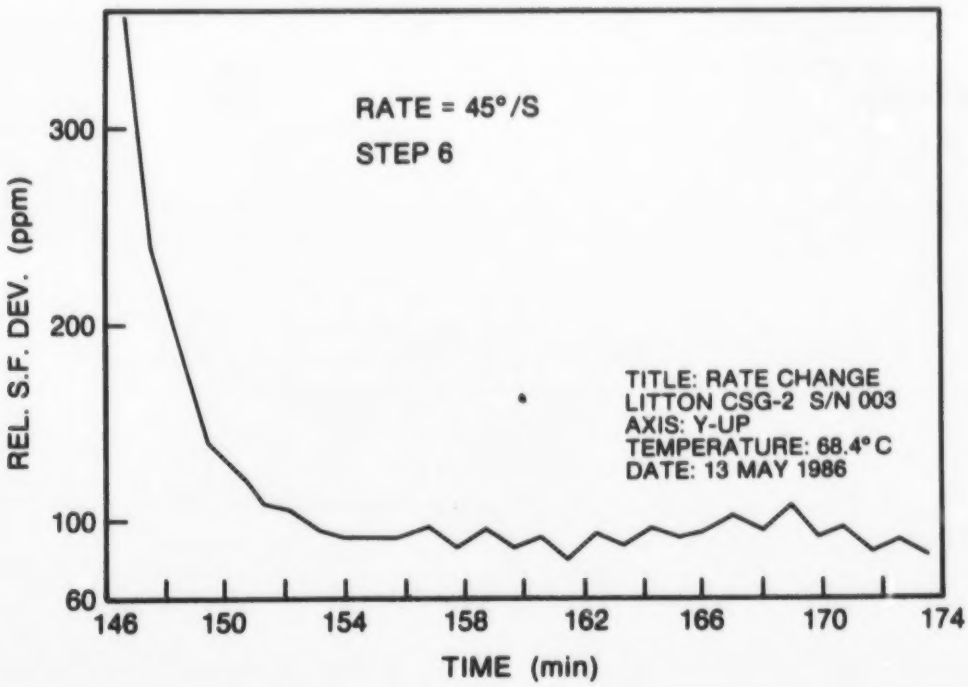

Figure 2-8. Single Rate Step, 30/45 deg/sec.

These results imply, therefore, that since the torquer scale factor temperature sensitivity is due almost exclusively to magnet properties, the scale factor deviation should be compensatable. Several options are possible. Physical compensation within the rotor assembly such as 'magnet compensators' would prove costly due to gyro design changes. In addition, compensating magnets would tend to shunt away some of the magnetic field strength resulting in a decreased torquer scale factor.

External compensation could be performed either at the gyro preamplifier or, perhaps most effectively, in software external to the instrument. The insertion of a temperature sensor into the gyro at the magnet location would permit precise measurement of the temperature and allow this external compensation.

Another possible solution is the changing of magnet material to samarium cobalt. $SmCo_5$ is the most popular magnet material but thermal sensitivity is only slightly better than platinum cobalt; -470ppm/°C and there is also a hydrogen absorption problem whereby the $SmCo_5$ magnet material degrades with time as a result of exposure to hydrogen within the gyroscope. The problem can be alleviated by plating of the $SmCo_5$ material and this option is being evaluated. Work is also being done with Sm_2Co_{17}, a samarium cobalt variation with inherently lower thermal sensitivity.

Another unique solution is to 'segment' the magnets within the gyro. The magnetic field strength can be greatly increased through this technique but problems can occur due to misalignment of the magnets; an assembly problem which could prove to be expensive.

All of the solutions provided here are viable but the driving factor will be the cost of the instrument and the accuracy required in a specific appliction.

3.0 CSG-2 PERFORMANCE SUMMARY

Table 3-1 contains a summary of the performance capabilities of the CSG-2 gyroscope.

Several design variations of the CSG-2 have been developed for various applications. These are listed in Table 3-2.

The CSG-2 has been incorporated into several (demonstration) operational systems including an Attitude and Heading Reference System (AHRS) where it's performance is now being evaluated for use in land vehicle, aircraft and helicopter applications.

PARAMETER		UNITS	SPECS	PERFORMANCE
Torquer Scale Factor	Kx	deg/hr/mA	1400	1642
	Ky	deg/hr/mA	1400	1671
Scale Factor Repeatability	Kx	Percent	0.01	
	ky	Percent	0.01	
Scale Factor Temp. Sensitivity	TKx	PPM/^{o}C		500
	TKy	PPM/^{o}C		500
Resonant Frequency (VERT)	FRv	Hz(Mech)	102 $\pm$ 2.5	105.5
(HORZ)	FRh	Hz(Mech)	102 $\pm$ 2.5	-
Random Drift (Vert)	Xv	deg/hr	0.005	
(Horz)	Yv	deg/hr	0.005	
	Xh	deg/hr	0.005	.0017
	Yh	deg/hr	0.005	.0014
Non g-Sensitive Drift	BDx	deg/hr	$\pm$ 3.0	-1.43
	BDy	deg/hr	$\pm$ 3.0	+5.14
Non g-Sensitive Repeatability	Bx	deg/hr	0.02	
	By	deg/hr	0.02	
g-Sensitive Drift	MUx	deg/hr/g	$\pm$10.0	+3.35
	Muy	deg/hr/g	$\pm$ 10.0	+3.36
	Qx	deg/hr/g	$\pm$ 10.0	-1.64
	Qy	deg/hr/g	$\pm$ 10.0	+1.55
g-Sensitive Repeatability	MUx	deg/hr/g	0.02	
	MUy	deg/hr/g	0.02	
Anisoelasticity (g^2-Sensitive)		deg/hr/g^2	0.05	.022
Motor Start Power (10 Volts)		Watts	8.0	7.5
Motor Run Power (5 Volts)		Watts	3.0	2.0
Time Constant		Sec	50	108
Pickoff Scale Factor	KPOx	V_{RMS}/m RAD	1.3 $\pm$ 20%	.716
	KPOy	V_{RMS}/m RAD	1.3 $\pm$ 20%	.720

Table 3-1 CSG-2 Performance Summary
(January, 1988)

PARAMETER	CSG-2 HIGH RATE	CSG-2A SPACE APPLICATIONS	CSG-2B AHRS APPLICATIONS
Random drift (^{o}Hr)	.005	.005	.005
Non-G sensitive drift (^{0}/Hr) 1	3.0	3.0	3.0
Non-G drift repeatability (^{0}/Hr/g)	0.02	0.2	0.02
G-sensitivity drift repeatability (^{0}Hr/g)1	0.02	0.02	0.02
Wheel speed (Hz) (Tuned freq)	100 $\pm$5	175 $\pm$5	100 $\pm$5
Torquer scale factor ^{0}/Hr/mA	1600	110	775
Torquer resistance (ohms) max	50	11	50
Torquer axis alignments (mRad)	20	20	20
Motor power start (watts) max run	7.25 1.56	5.0 1.0	5.0 1.0
Nominal operating temperature	155^{o}F	155^{0}F (60^{0}F-200^{0}F) Design range	155^{0}F

Table 3-2
CSG-2 Version Specifications

References

1. 'Test Evaluation of the Litton (Canada) Canadian Strapdown Gyroscope (CSG-2)', Vinnins, Gallop, Paquet; DREO Report #914, September, 1986.

2. 'The CSG-2 Canadian Strapdown Gyroscope; Rate and Dynamic Test'; Gallop, Vinnins, Sinkiewicz; Symposium Gyro Technology, Stuttgart, September, 1987.

3. 'Rate and Dynamic Tests on the Canadian Strapdown Gyroscope (CSG-2)'; Vinnins, Gallop, Paquet; 13th Biennial Guidance Test Symposium, Holloman AFB, NM, October, 1987.

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(Security classification of title, body of abstract and indexing annotation must be entered when the overall document is classified)

1. ORIGINATOR (the name and address of the organization preparing the document. Organizations for whom the document was prepared, e.g. Establishment sponsoring a contractor's report, or tasking agency, are entered in section 8.)

Defence Research Establishment Ottawa
NDHQ
Ottawa, Canada K1A 0Z4

2. SECURITY CLASSIFICATION (overall security classification of the document. including special warning terms if applicable)

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3. TITLE (the complete document title as indicated on the title page. Its classification should be indicated by the appropriate abbreviation (S,C,R or U) in parentheses after the title.)

Analysis of Rate and Dynamic Tests on the Litton (Canada) Canadian Strapdown Gyroscope (CSG-2)

4. AUTHORS (Last name, first name, middle initial)

Vinnins, Michael F, Gallop, Lloyd D

5. DATE OF PUBLICATION (month and year of publication of document)

December, 1987

6a. NO. OF PAGES (total containing information. Include Annexes, Appendices, etc.)

25

6b. NO. OF REFS (total cited in document)

3

7. DESCRIPTIVE NOTES (the category of the document, e.g. technical report, technical note or memorandum. If appropriate, enter the type of report, e.g. interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered.)

Technical Note 88-20

8. SPONSORING ACTIVITY (the name of the department project office or laboratory sponsoring the research and development. Include the address.)

9a. PROJECT OR GRANT NO. (if appropriate, the applicable research and development project or grant number under which the document was written. Please specify whether project or grant)

041LJ

9b. CONTRACT NO. (if appropriate, the applicable number under which the document was written)

10a. ORIGINATOR'S DOCUMENT NUMBER (the official document number by which the document is identified by the originating activity. This number must be unique to this document.)

10b. OTHER DOCUMENT NOS. (Any other numbers which may be assigned this document either by the originator or by the sponsor)

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13. ABSTRACT (a brief and factual summary of the document. It may also appear elsewhere in the body of the document itself. It is highly desirable that the abstract of classified documents be unclassified. Each paragraph of the abstract shall begin with an indication of the security classification of the information in the paragraph (unless the document itself is unclassified) represented as (S), (C), (R), or (U). It is not necessary to include here abstracts in both offical languages unless the text is bilingual).

Results of rate and dynamic tests on the Litton (Canada) Canadian Strapdown Gyroscope (CSG-2) are presented. Tests include scale factor stability, scale factor deviation at constant rate over a rate range of ± 1 radian/sec, rate change (transient) tests as well as evaluation of the effects of temperature changes. Instrument design characteristics and suggestions for future improvements are discussed.

14. KEYWORDS, DESCRIPTORS or IDENTIFIERS (technically meaningful terms or short phrases that characterize a document and could be helpful in cataloguing the document. They should be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location may also be included. If possible keywords should be selected from a published thesaurus. e.g. Thesaurus of Engineering and Scientific Terms (TEST) and that thesaurus-identified. If it is not possible to select indexing terms which are Unclassified, the classification of each should be indicated as with the title.)

Inertial Navigation
Strapdown Gyroscope
Tuned Rotor Gyroscope
Two-degree-of-freedom Gyroscope

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